A Method for Snow Reanalysis: The Sierra Nevada (USA) Example

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Presentation outline

- **Motivations**
- A Method for Snow Reanalysis
- Proof of Concept: Sierra Nevada Case
- Conclusions

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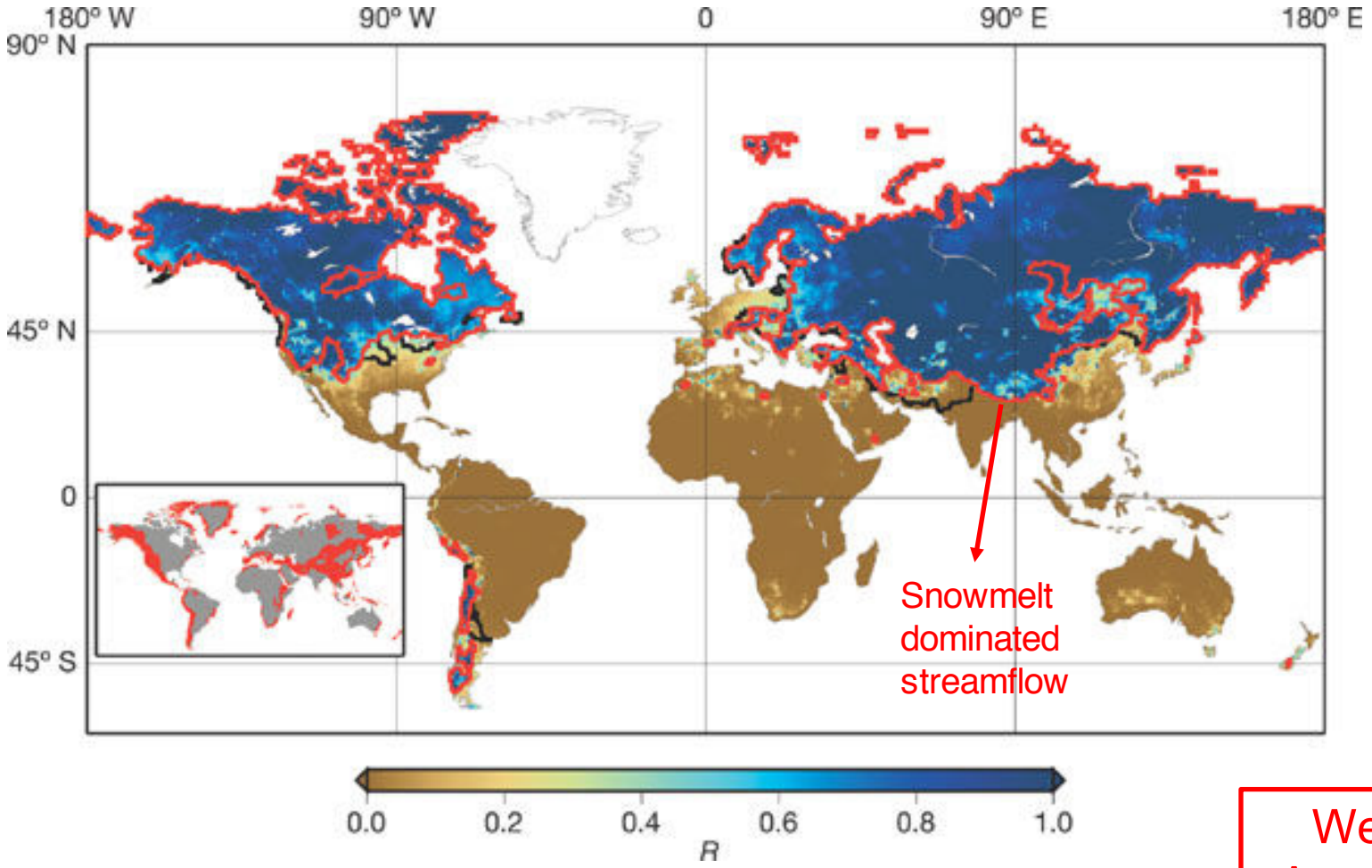
Importance of Snow



Barnett et al., (2005), Nature

Water Balance Prospective:

- Water Reservoir
- Snow Water Equivalent

(**SWE**, i.e. the amount of water stored as snow)

Energy Balance Prospective:

- High Snow Albedo

(Strong influence on land-atmosphere interaction, weather and climate feedbacks)

We need accurate estimates of **SWE** → Accurate water, weather, climate forecasts.

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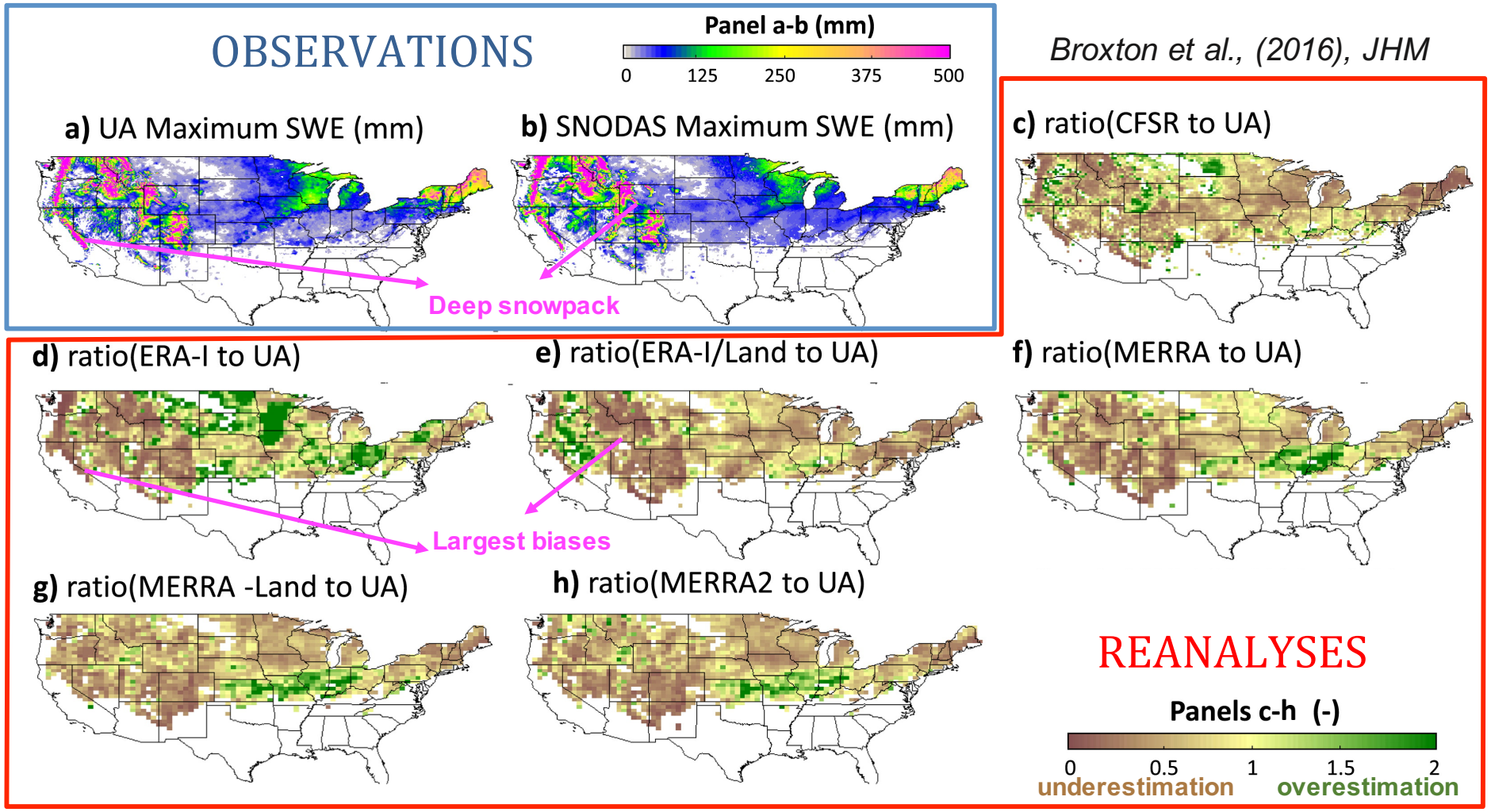
Snow Bias in Global Reanalysis Datasets



Broxton et al., (2016), JHM

- SWE is underestimated
- Larger biases in deep snowpack
- Biases marginally explain by spatial resolution and snowfall biases

Need to provide unbiased reanalysis estimates of SWE

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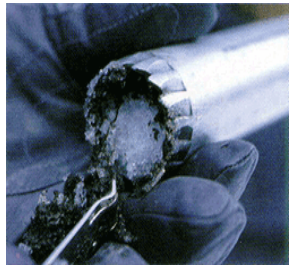
Snow Observations

- **In-Situ Observations**

e.g., snow-pillow, courses



  - Direct Observations
  - Sparse in Space/Time
  - Insufficient (global) Network

- **Satellite Observations**

1) Passive Microwave (e.g., **SSM/I; AMSRE-E**)

  - All weather
  - Daily, 25 km
  - 1987 – present
  - Sensitive to Snow Depth
  - But only shallow SWE

2) Visible/Near-infrared (e.g., **Landsat, MODIS**)

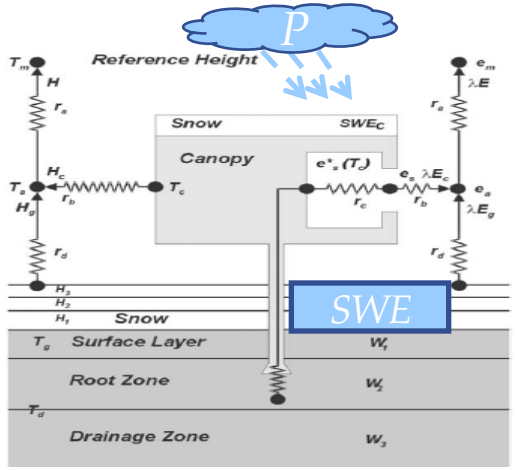
  - Daily-Weekly, sub-km scales
  - 1984 – present
  - Clear-sky only
  - No direct estimate of SWE
  - Only Fractional Snow Cover Area (**FSCA**)

Snow Modeling

Snow processes are known to be a **weakness** of land surface modeling:

- Insufficient winter precipitation forcings
- Complexity of Mountainous Environments

But, models are **good** because providing continuous (space/time) estimates of **SWE** and **FSCA**



None of these streams can (alone) provide accurate estimates of SWE

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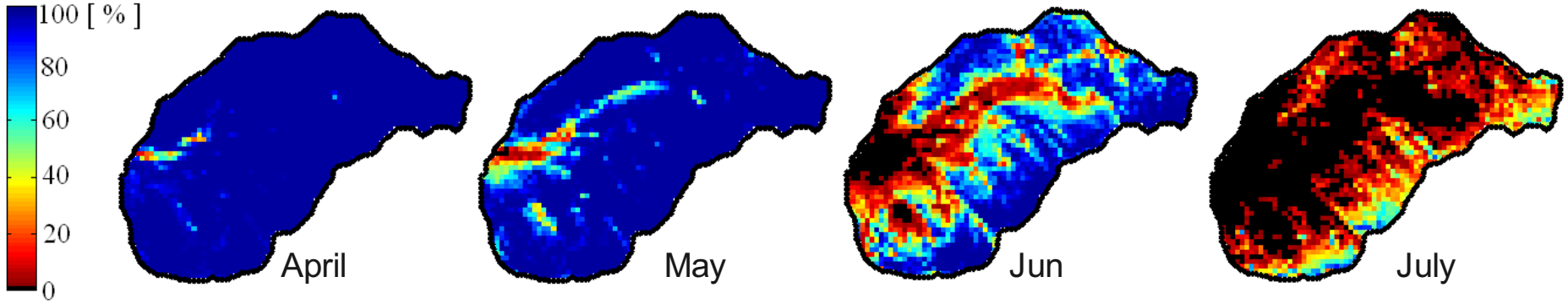
Snow Reanalysis Concept

Example FSCA depletion
(Tokopah Watershed, California)

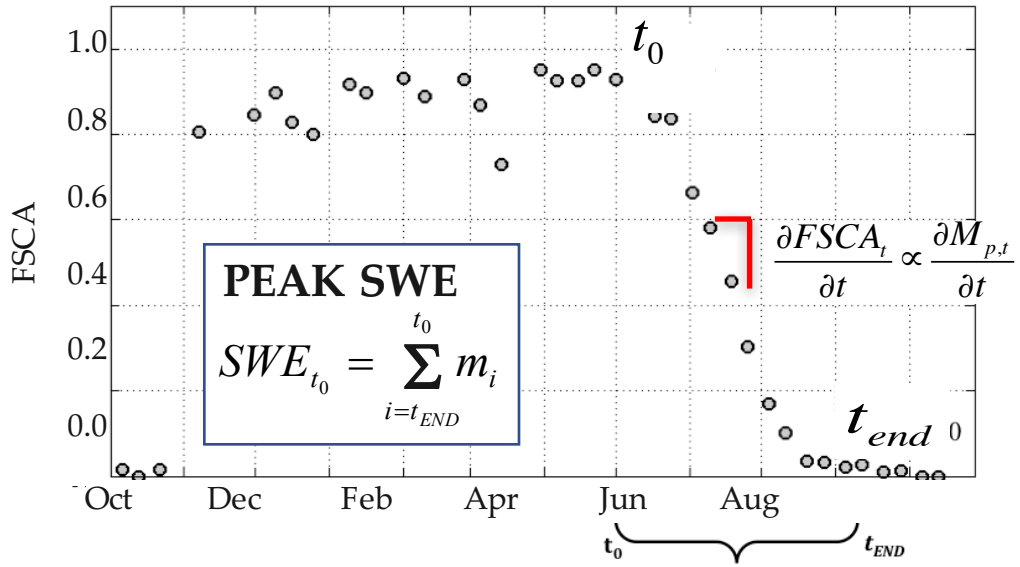


Reconstruction of SWE from:

- Depletion of fractional snow covered area [***FSCA***]
- Space/Time continuous energy fluxes
- SWE as a sum of melt (m_i) events

Use satellite observed FSCA to estimate SWE!!

Girotto et al. (2014); HP



Cline et al. (1998), WRR

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Snow Reanalysis Concept

Example FSCA depletion
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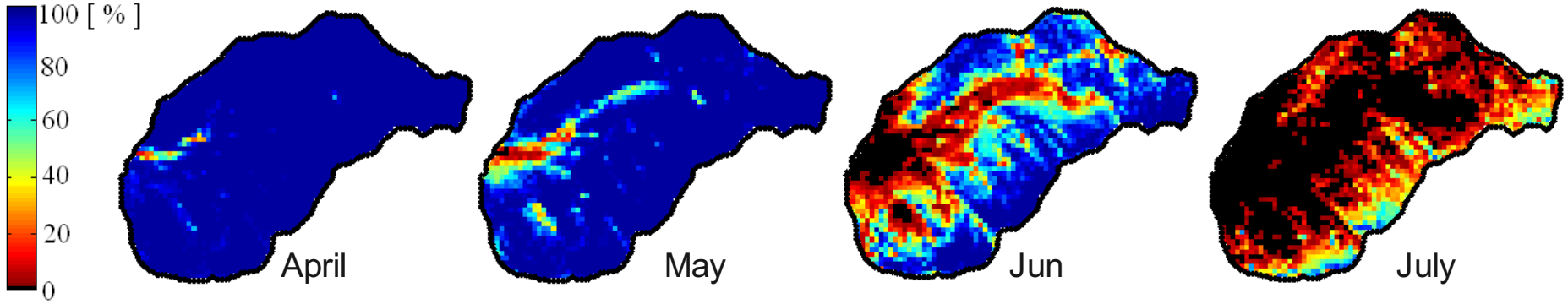

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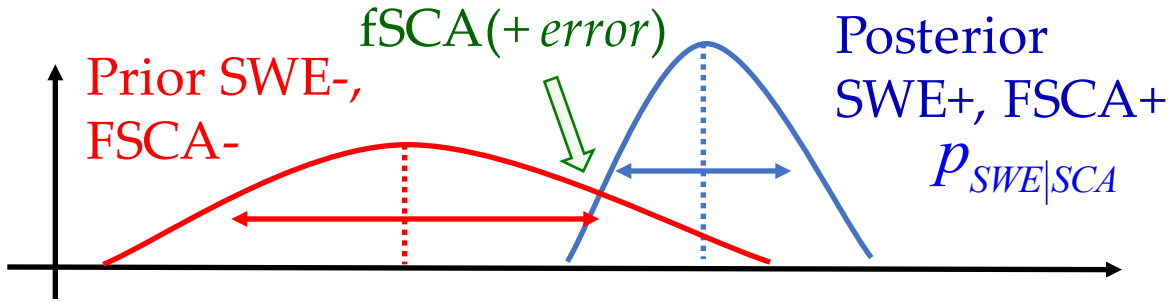
Probabilistic Approach
(Ensemble Kalman Smoother)



Girotto et al. (2014); HP

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Sequential vs. Smoothing Schemes

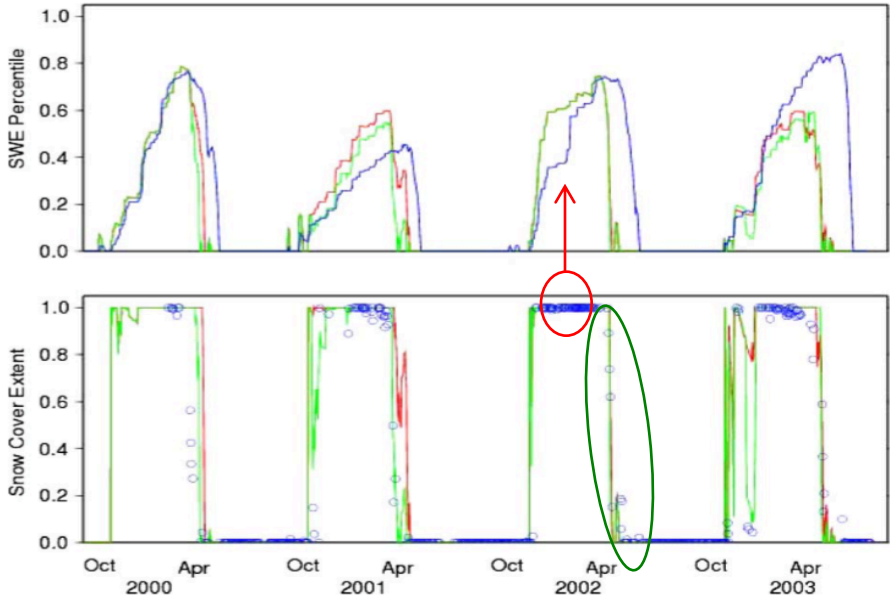
Sequential schemes (e.g., EnKF)

$$[\Delta x]_t = K_t [M(x^-) - obs]_t$$
$$K_t = C_{xM|t} [C_{MM} + R]_t^{-1}$$

t: time when the obs is available!

Obs = fSCA ; $\Delta x = \Delta SWE$; C_{xM} Relies on instant. fSCA ←→SWE

Obs.
OL
DA



Andreadis and Lettenmaier (2006), AdWR

Good for ephemeral SWE only;
weak correlation fSCA ← → SWE for deep SWE

Smoother schemes (e.g., EnKS, or PS)

$$[\Delta x] = K [M(x^-) - obs]$$
$$K = C_{xM}[C_{MM} + R]\text{-}1$$

Obs = fSCA for the **entire ablation season**

$\Delta x = \Delta SWE$; C_{xM} obtained from a batch of fSCA ←→SWE

- Deeper snowpacks
- No real-time applications
- Useful in for reanalysis

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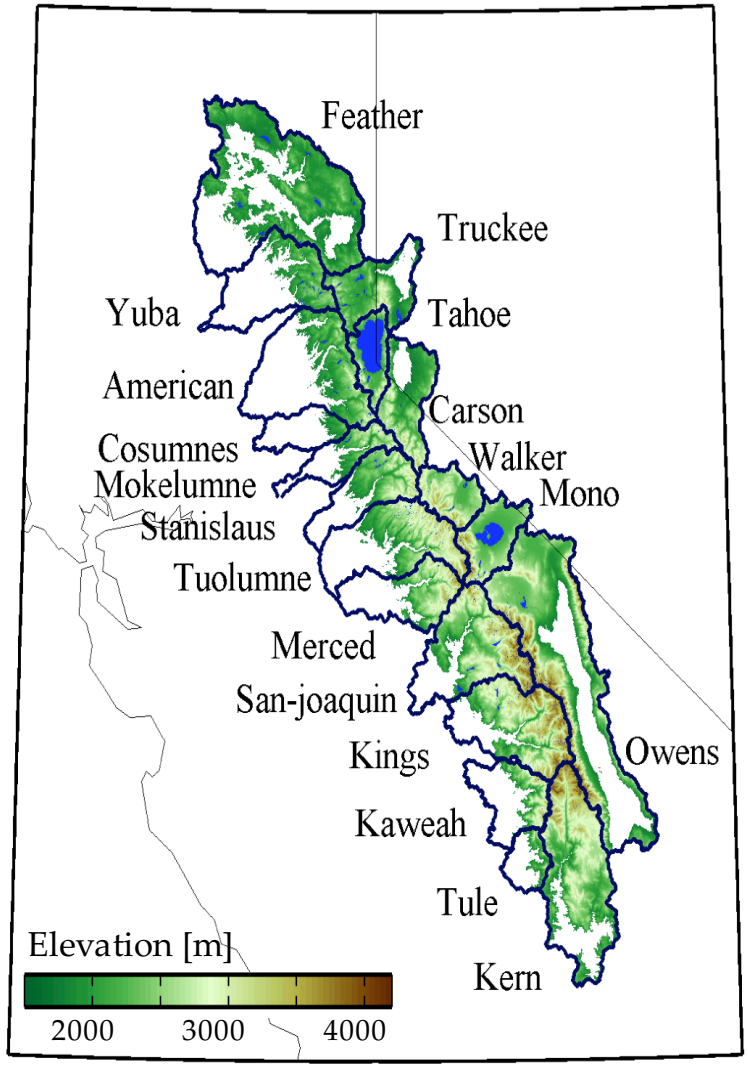
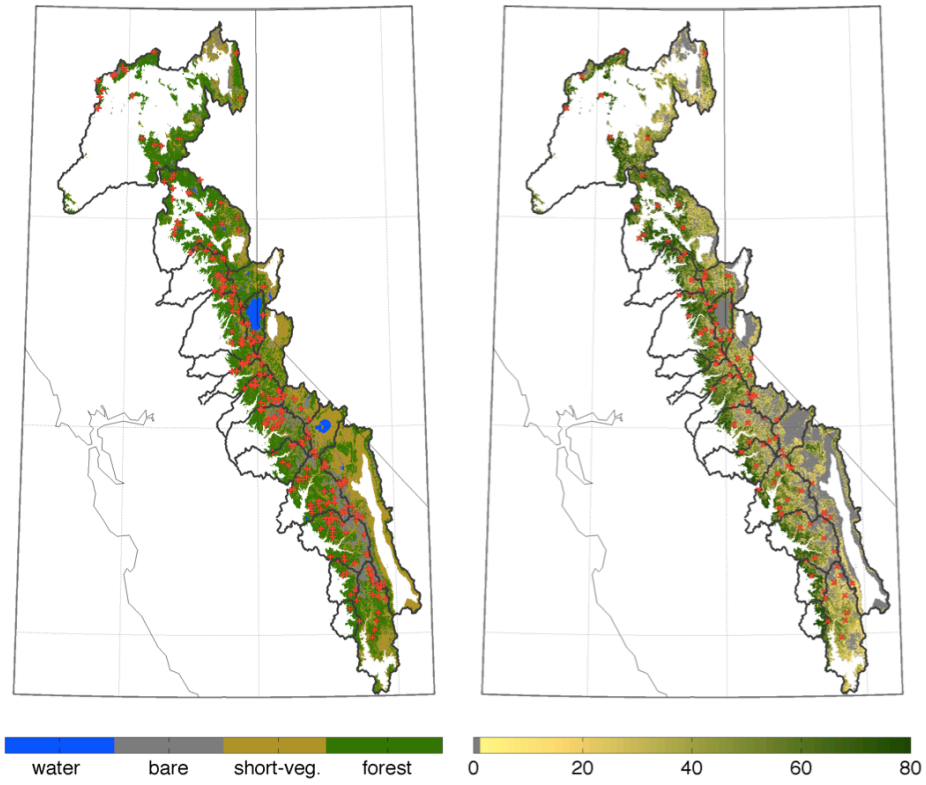
The Sierra Nevada Example

- Landsat observations
  (Landsat 5-8 record)
- Forcings: NLDAS
- Temporal Extent: **31 years**
- Spatial resolution: **90 m**
- Temporal resolution: **daily**
- Analysis: Particle Smoother
- Maritime snowpack (max. SWE ~1-2m)



- Validation:

- 108 snow-pillow
- 202 snow-courses



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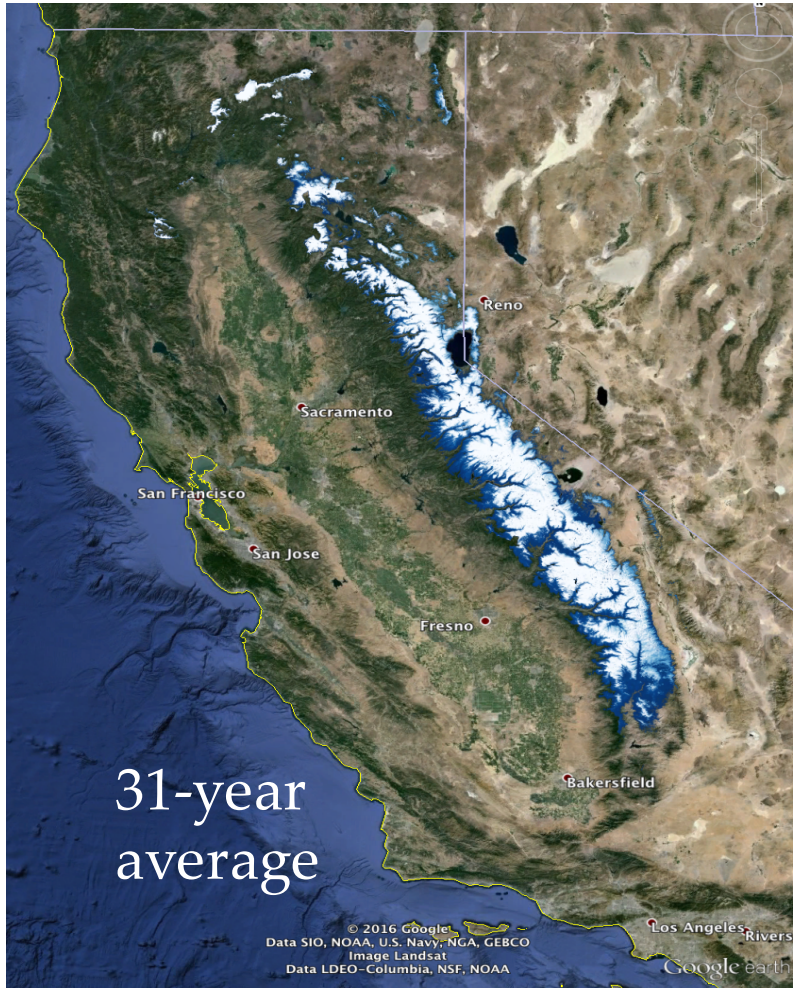

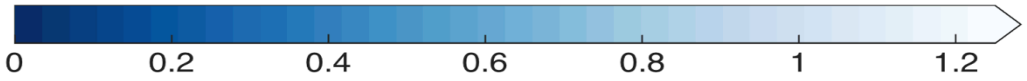

Water Year (WY): Oct. 1st-Sept. 30th

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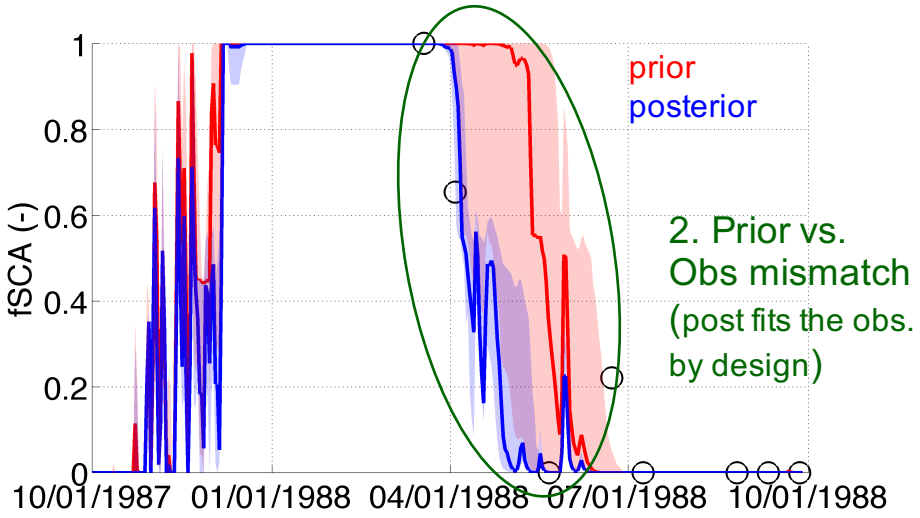
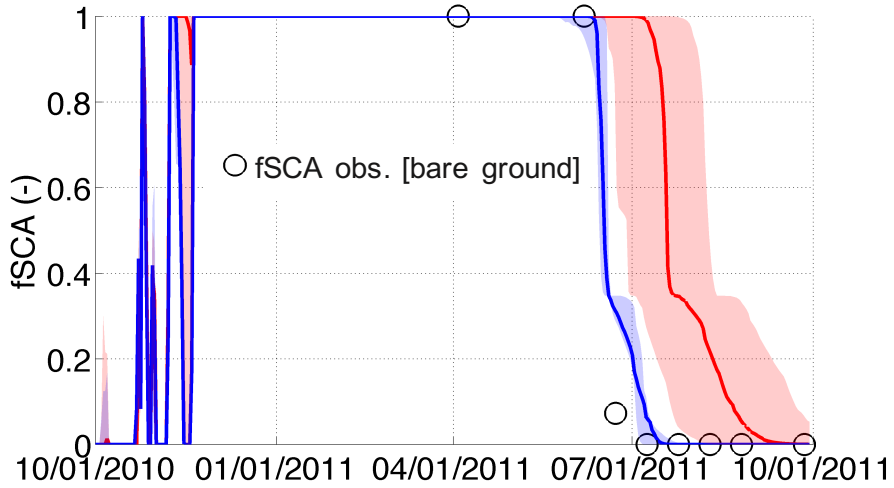
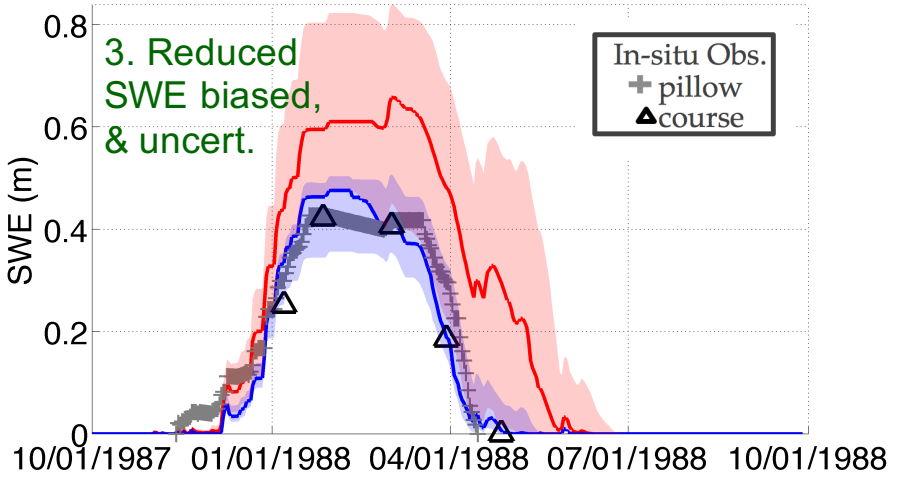
The Sierra Nevada Example

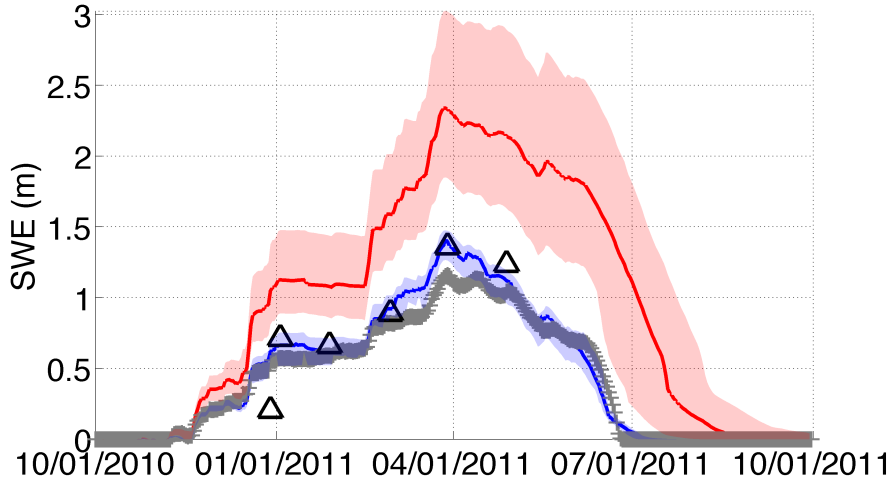




dry year

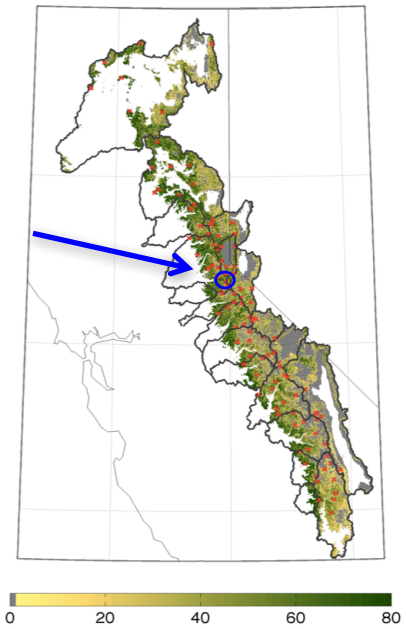


wet year



Example: American River Watershed:

- fveg = 52%,
- elev=2400 m;
- co-located pillow/snow course data



(Margulis et al. 2016; JHM)

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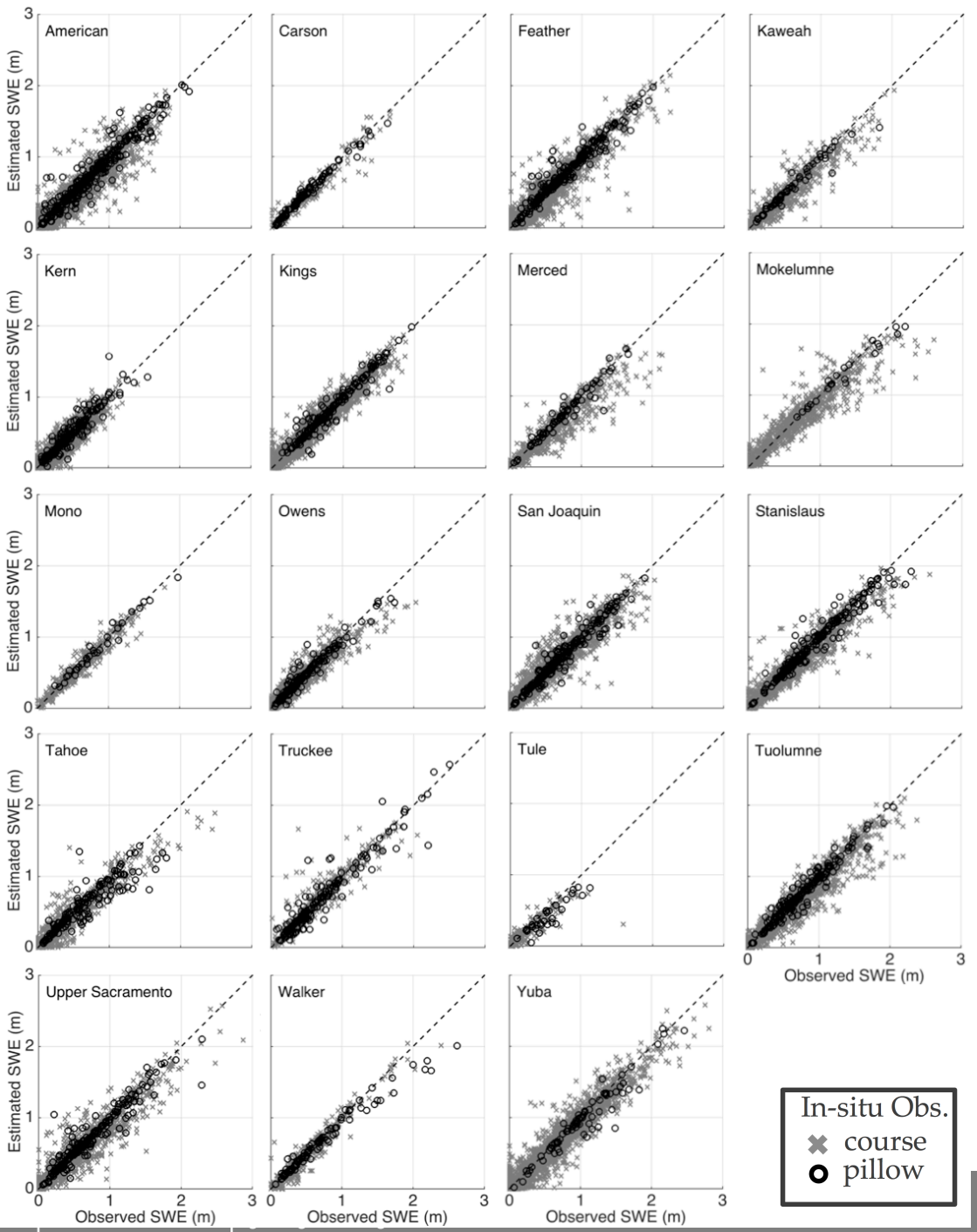
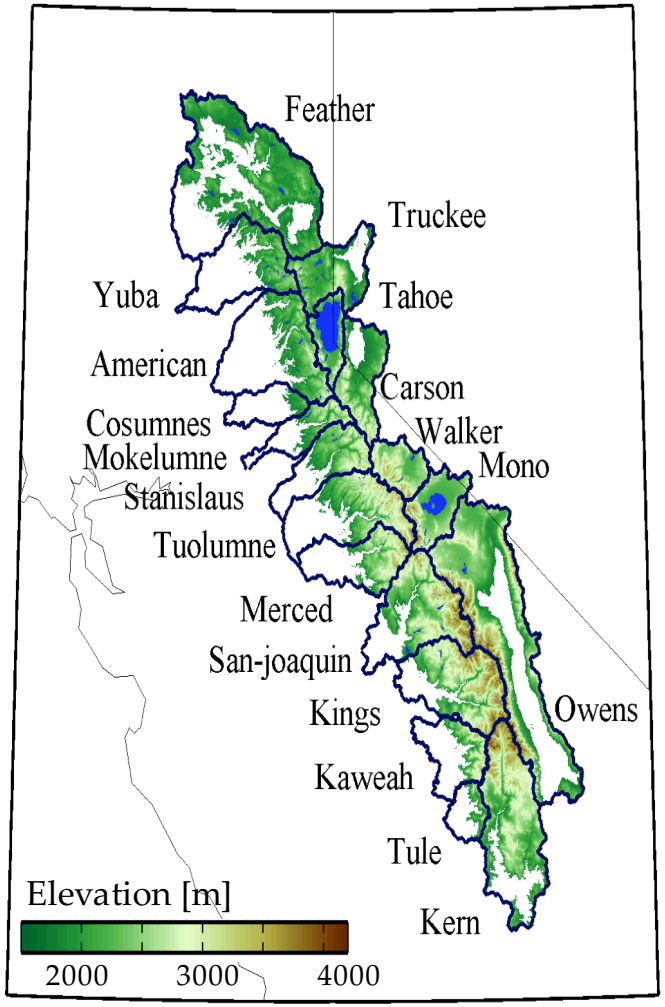
The Sierra Nevada Example



SWE estimates validated against >9000 station-years (snow pillow & snow course data)

SWE statistics show encouraging results:

- ME ~ -2 cm
- RMSE ~ 12 cm
- Corr. ~ 0.96



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Conclusions & Future Directions

- This SWE reanalysis provides **unbiased** estimates of SWE even for **large snowpacks** (at least for the Sierra Nevada Mountains)
- SWE reanalysis provides an **unique** dataset in terms of large spatial/temporal extent, high spatial/temporal resolution, accuracy
- Batch (or **smoothing**) approaches need to be used (as opposed to sequential techniques) to assimilate the entire FSCA depletion
- The next step is to test the validity of the methods for **global reanalysis**

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Thanks!!!

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